Regionalization of climate and crop yields on the example of Bulgaria

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Abstract

The objectives of the present article are to use the last developments in climate classification to make regionalization of climate in Bulgaria and to contribute to the agricultural economics of the country by linking the yields of basic agricultural crops with the climate classification. The geographical area covers between 22 and 29 degrees East longitude and 41 and 44.5 degrees North latitude. Materials are monthly climatic data - mean temperature and precipitation for selected Bulgarian locations and survey yields of four crops — winter wheat, barley, maize, and sunflower. The study is based on the extraction of the new and improved Köppen-Geiger climate classification map for the present (1980−2016). Extensive use of Geographic Information Systems (GIS) and advanced statistical methods and software allows obtaining reliable results and their appropriate interpretation. Regression equations present the dependent variable yield of crops as a function of Köppen classes. The study provides guidance on the ecological zoning of agricultural crops. The tables and figures included illustrating the findings of the study. Results are related to the territory of Bulgaria, but the approach is applicable everywhere in the world.

Key words. Köppen-Geiger climate classification, crops zoning, GIS, statistical analysis.

INTRODUCTION

First August Grisebach [11] published a Map of the vegetation areas of the Earth, which presented the climatically conditioned analogous areas in the Mediterranean, California, Chile, Australia, and South Africa. He described the geography of the plants and their dependence on the climate [12]. One generation later the German scientist Wladimir Köppen made attempt to present the first quantitative classification of world climates [15]. In Issue 5 of the "Geographical Writings" edited by him has Alfred Hettner published "Die Klimate der Erde" and provided 14 climates [13]. A critical evaluation and further development on the issue of climate classification was made by Köppen, which gives key and diagrams for the determination of the climate formula [16]. A revision of the classification was made by Rudolf Geiger [10]. A huge number of climate studies and subsequent publications adopted this or a former release of the Köppen-Geiger map [14].

Some authors focus on definitions of climate types according to the Köppen-Trewartha climate classification (KTC) with special attention given to the distinction between wet and dry climates. The distribution of KTC types is compared with the original Köppen classification (KCC) for the period 1961−1990 [4].

The comparison of classification results achieved for individual 15-year intervals with the spatial distribution of climate classes obtained based on the whole 1951 − 2000 period reveals that the most recent sub-period from 1986 − 2000 shows the greatest deviations to the long-term mean climate in terms of area fractions of different climate types [2]. The work of D. Chen and H. Chen [6] used a global temperature and precipitation observation dataset to reveal variations and changes of climate over the period 1901-2010, demonstrating the power of the Köppen classification in describing not only climate

change but also climate variability on various temporal scales.

It is noteworthy that the Köppen classification system is based on the strong dependence of natural vegetation on climate. Natural plants integrate many effects of climate, particularly expressing the adequacy of moisture under a given set of temperature conditions [7]. As stated by Critchfield, the crucial point is the purpose for which a systematic arrangement of climates is intended.

The regionalization facilitates (1) planning at the national level, where it is necessary to study management problems and potential solutions on a regional basis; (2) organization and retrieval of data gathered in a resource inventory; and (3) interpretation of inventory data, including differences in indicator plants and animals among regions [1]. The GIS-based regionalization of Pakistan's annual and seasonal temperatures and rainfalls describes the sub-regional distribution of climate parameters across Pakistan [22]. The work was carried out by analyzing 30-year climatic normal data (from 1981 to 2010) to classify the patterns of climate parameters across Pakistan and find out the climate classes at every 59 meteorological stations using the Köppen climate scheme.

The objectives of the present article are to use the last developments in climate classification to make regionalization of climate in Bulgaria and to contribute to the agricultural economics of the country by linking the yields of basic agricultural crops with the climate classification. The study provides guidance on the ecological zoning of agricultural crops. Results are related to the territory of Bulgaria, but the approach is applicable everywhere in the world.

MATERIAL AND METHODS

Monthly climatic data - mean temperature and precipitation for 238 selected Bulgarian locations [5] were used by Köppen Climate Classifier [17]. It is a simple computer program, which requires the selection of the northern or southern hemisphere and the average monthly temperatures and monthly precipitation for each location are entered, and as a result: the highest, lowest, and average temperatures, highest, lowest, and average precipitations and Köppen class are obtained. Statistical properties of the first set of data are given in Table 1.

As a result after the input of available data to the Climate Classifier five climate classes were identified:
14-Cfa, 15-Cfb, 25-Dfa, 26-Dfb, and 29-ET.

A new global map of climate using the Köppen -Geiger system was produced based on a large global data set of long-term monthly precipitation and temperature station time series. Climatic variables used in the Köppen -Geiger system were calculated at each station and interpolated between stations using a two-dimensional (latitude and longitude) thin-plate spline with tension onto a 0.1°×0.1° grid for each continent [20]. It is appropriate to cite their remark: In Europe, some climate types are extending further than expected due to a low density of temperature stations. For example, around pick Musala (Coordinates: 42°10′47″N, 23°35′12″E, Elevation 2,925.4 m), Bulgaria there is a region of ET climate type. There are three temperature stations within this ET region, which are all located at over 2000 m in elevation, and their observations confirm an ET climate type. However, rather than being part of a single range of mountains, these three stations are located on top of three separate peaks with extensive lowlands in between. As there are no temperature stations located in the lowlands the splines ignore them and the entire region is set to ET, rather than a mixture of ET and Df.

Continuation of our study is based on the new and improved Köppen-Geiger climate classification map for the present (1980–2016) with an unprecedented 0.0083° resolution (approximately 1 km at the

equator), providing a more accurate representation of highly heterogeneous regions [3]. The maps are referenced to the World Geodetic Reference System 1984 (WGS 84) ellipsoid. The maps are stored in the GeoTIFF format. The file contains a table with dimensions 21600 × 43200 (rows × columns). The first two columns give the center grid coordinates and the third is the numeric value of the Köppen-Geiger classes. The maps can be visualized and analyzed using most Geographic Information Systems (GIS) software.

We are using QGIS 3.10 GNU GPL package [21]. With its help raster conversion to XYZ file was performed and the resulting file in CVS format with 9,331,200 rows is too large for Excel to handle. Files with more than 1 million rows (technically more than 1,048,576 rows) are possible to process with specialized software as Delimit 4.1 [8]. With this software, we succeeded to reduce the file size to cover the geographical area of Bulgaria (22-29 degrees E, 41-44.5 degrees N). With QGIS feature raster by extent extraction, we receive the GeoTIFF file ready

for conversion to Excel XYZ file, which contains 3244 locations with the Köppen-Geiger classes. The statistical properties of the second set of data are presented in Table 2.

As a result of the described procedure eleven climate classes were identified:
7-BSk, 8-Csa, 9-Csb, 14-Cfa, 15-Cfb, 18-Dsb, 19-Dsc, 25-Dfa, 26-Dfb, 27-Dfc, 29-ET.

To make a graphical presentation of the results Surfer [23] contouring, gridding, and surface mapping package was used. Surfer is a grid-based mapping program that interpolates irregularly spaced XYZ data into a regularly spaced grid. The geographical area of Bulgaria covers between 22 and 29 degrees East longitude and 41 and 44.5 degrees North latitude. A base map containing XY location data about the boundary of Bulgaria and its 28 districts is used in image format. Kriging gridding method is applied to give good results producing grid file and contour map that is two-dimensional representations of three-dimensional data.

Table 1. Statistical description of the first set of data (N = 238)

Variable	Mean	Median	Minimum	Maximum	Std.Dev.	Skewness	Kurtosis
Wheat	3393.4	3390.2	2833.1	4152.9	504.954	0.152	-1.488
Barley	3162.4	3294.1	2579.7	3724.5	465.748	-0.202	-1.704
Maize	4482.7	4295.5	4127.6	4908.2	305.946	0.276	-1.632
Sunflower	1829.4	1751.5	1579.1	2088.6	208.260	0.069	-1.774

Table 2. Statistical description of the second set of data (N = 3244)

Variable	Mean	Median	Minimum	Maximum	Std.Dev.	Skewness	Kurtosis
Wheat	3387.7	3390.2	0.0	4152.9	552.965	-0.818	4.170
Barley	3156.0	3294.1	0.0	3724.5	508.276	-1.133	4.339
Maize	4462.4	4295.5	0.0	4908.2	425.429	-4.798	49.756
Sunflower	1817.9	1751.5	0.0	2088.6	235.934	-1.837	12.958

Table 3. Legend linking the numeric values in the maps to the Köppen-Geiger classes.

No	Code	Name	Color	RGB
1	Af	Tropical, rainforest		[0 0 255]
2	Am	Tropical, monsoon		[0 120 255]
3	Aw	Tropical, savannah		[70 170 250]
4	BWh	Arid, desert, hot		[255 0 0]
5	BWk	Arid, desert, cold		[255 150 150]
6	BSh	Arid, steppe, hot		[245 165 0]
7	BSk	Arid, steppe, cold		[255 220 100]
8	Csa	Temperate, dry summer, hot summer		[255 255 0]
9	Csb	Temperate, dry summer, warm summer		[200 200 0]
10	Csc	Temperate, dry summer, cold summer		[150 150 0]
11	Cwa	Temperate, dry winter, hot summer		[150 255 150]
12	Cwb	Temperate, dry winter, warm summer		[100 200 100]
13	Cwc	Temperate, dry winter, cold summer		[50 150 50]
14	Cfa	Temperate, no dry season, hot summer		[200 255 80]
15	Cfb	Temperate, no dry season, warm summer		[100 255 80]
16	Cfc	Temperate, no dry season, cold summer		[50 200 0]
17	Dsa	Cold, dry summer, hot summer		[255 0 255]
18	Dsb	Cold, dry summer, warm summer		[200 0 200]
19	Dsc	Cold, dry summer, cold summer		[150 50 150]
20	Dsd	Cold, dry summer, very cold winter		[150 100 150]
21	Dwa	Cold, dry winter, hot summer		[170 175 255]
22	Dwb	Cold, dry winter, warm summer		[90 120 220]
23	Dwc	Cold, dry winter, cold summer		[75 80 180]
24	Dwd	Cold, dry winter, very cold winter		[50 0 135]
25	Dfa	Cold, no dry season, hot summer		[0 255 255]
26	Dfb	Cold, no dry season, warm summer		[55 200 255]
27	Dfc	Cold, no dry season, cold summer		[0 125 125]
28	Dfd	Cold, no dry season, very cold winter		[0 70 95]
29	ET	Polar, tundra		[178 178 178]
30	EF	Polar, frost		[102 102 102]

Table 4. Assignment of dummy variables to classes

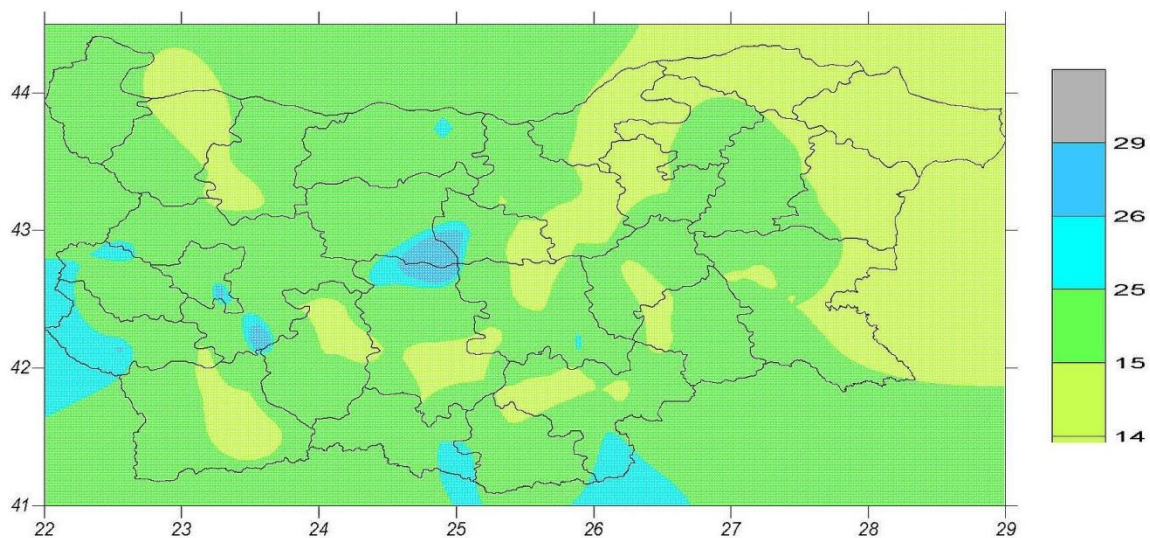|	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11
BSk	1	0	0	0	0	0	0	0	0	0	0
Csa	0	1	0	0	0	0	0	0	0	0	0
Csb	0	0	1	0	0	0	0	0	0	0	0
Cfa	0	0	0	1	0	0	0	0	0	0	0
Cfb	0	0	0	0	1	0	0	0	0	0	0
Dsb	0	0	0	0	0	1	0	0	0	0	0
Dsc	0	0	0	0	0	0	1	0	0	0	0
Dfa	0	0	0	0	0	0	0	1	0	0	0
Dfb	0	0	0	0	0	0	0	0	1	0	0
Dfc	0	0	0	0	0	0	0	0	0	1	0
ET	0	0	0	0	0	0	0	0	0	0	1

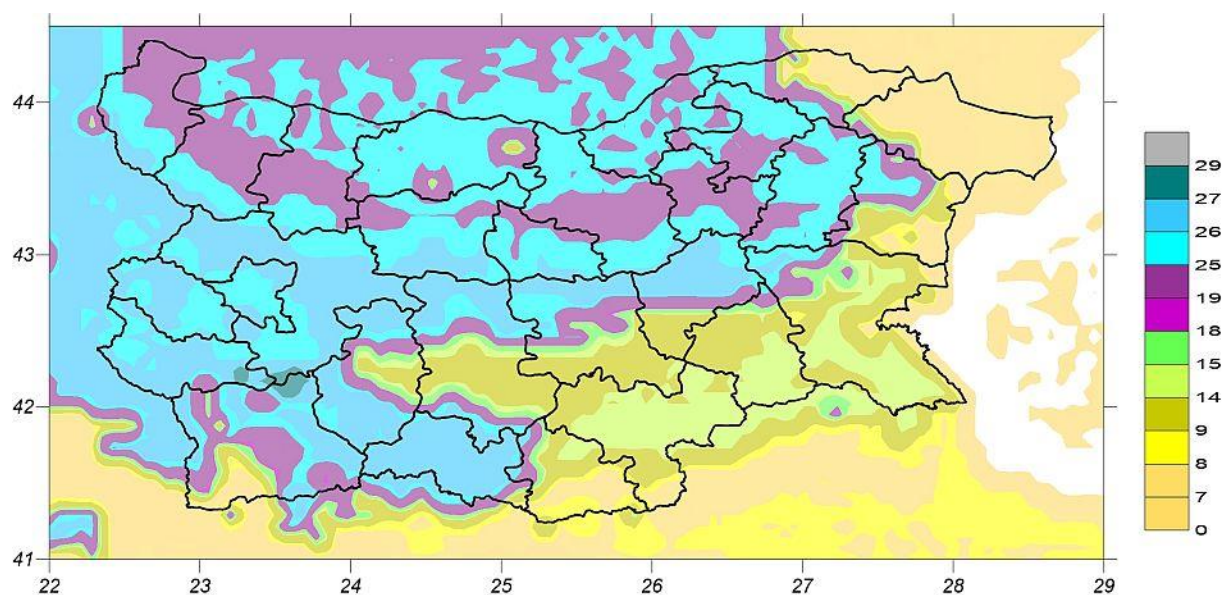Figure 1. Climate regionalization of Bulgaria (first approximation)

Figure 2. Climate regionalization of Bulgaria (second approximation)

Table 5. Regression summary for the dependent variable yield of wheat.

Code	b	Std.Err	t	p	-95% Cnf.Lmt	+95% Cnf.Lmt
BSk	3912.040	26.013	150.386	0.000	3861.035	3963.044
Csa	-1019.574	43.266	-23.565	0.000	-1104.406	-934.742
Csb	-1070.628	162.036	-6.607	0.000	-1388.331	-752.925
Cfa	-697.759	29.139	-23.946	0.000	-754.891	-640.627
Cfb	-606.368	66.621	-9.102	0.000	-736.991	-475.746
Dsb	-1078.403	93.113	-11.582	0.000	-1260.971	-895.836
Dsc	-1078.922	137.649	-7.838	0.000	-1348.811	-809.033
Dfa	-60.285	28.352	-2.126	0.034	-115.874	-4.695
Dfb	-803.599	28.146	-28.551	0.000	-858.785	-748.412
Dfc	-1076.482	90.553	-11.888	0.000	-1254.030	-898.935
ET	-3912.040	99.056	-39.493	0.000	-4106.258	-3717.821

Table 6. Regression summary for the dependent variable yield of barley.

Code	b	Std.Err	t	p	-95% Cnf.Lmt	+95% Cnf.Lmt
BSk	3550.278	24.548	144.624	0.000	3502.146	3598.410
Csa	-850.686	40.830	-20.835	0.000	-930.741	-770.632
Csb	-910.101	152.911	-5.952	0.000	-1209.914	-610.289
Cfa	-492.921	27.498	-17.926	0.000	-546.836	-439.007
Cfb	-482.619	62.869	-7.677	0.000	-605.886	-359.352
Dsb	-966.793	87.870	-11.003	0.000	-1139.079	-794.507
Dsc	-970.572	129.898	-7.472	0.000	-1225.262	-715.882
Dfa	23.332	26.755	0.872	0.383	-29.127	75.791
Dfb	-665.346	26.561	-25.049	0.000	-717.425	-613.267
Dfc	-952.787	85.454	-11.150	0.000	-1120.336	-785.237
ET	-3550.278	93.477	-37.980	0.000	-3733.559	-3366.997

Table 7. Regression summary for the dependent variable yield of maize.

Code	b	Std.Err	t	p	-95% Cnf.Lmt	+95% Cnf.Lmt
BSk	4746.961	14.882	318.970	0.000	4717.782	4776.141
Csa	-503.238	24.753	-20.331	0.000	-551.770	-454.705
Csb	-505.044	92.700	-5.448	0.000	-686.802	-323.287
Cfa	-444.619	16.670	-26.672	0.000	-477.304	-411.934
Cfb	-327.885	38.113	-8.603	0.000	-402.614	-253.156
Dsb	-612.178	53.270	-11.492	0.000	-716.624	-507.732
Dsc	-619.320	78.749	-7.864	0.000	-773.723	-464.917
Dfa	39.847	16.220	2.457	0.014	8.045	71.650
Dfb	-429.281	16.103	-26.659	0.000	-460.853	-397.709
Dfc	-585.710	51.805	-11.306	0.000	-687.284	-484.135
ET	-4746.961	56.670	-83.766	0.000	-4858.073	-4635.849

Table 8. Regression summary for the dependent variable yield of sunflower.

Code	b	Std.Err	t	p	-95% Cnf.Lmt	+95% Cnf.Lmt
BSk	1974.110	10.071	196.018	0.000	1954.363	1993.856
Csa	-377.210	16.751	-22.519	0.000	-410.053	-344.367
Csb	-394.992	62.732	-6.296	0.000	-517.991	-271.993
Cfa	-270.510	11.281	-23.979	0.000	-292.629	-248.392
Cfb	-201.803	25.792	-7.824	0.000	-252.374	-151.232
Dsb	-339.182	36.049	-9.409	0.000	-409.863	-268.501
Dsc	-335.461	53.291	-6.295	0.000	-439.949	-230.973
Dfa	50.702	10.976	4.619	0.000	29.181	72.224
Dfb	-240.702	10.897	-22.089	0.000	-262.067	-219.336
Dfc	-352.970	35.058	-10.068	0.000	-421.708	-284.233
ET	-1974.110	38.349	-51.477	0.000	-2049.301	-1898.918

Table 9. Statistical properties of regression equations

Crops	R	Adj. R^2	Std. Err.	F
Wheat	0.764	0.582	357.62	452.04
Barley	0.749	0.559	337.48	412.30
Maize	0.877	0.769	204.60	1078.90
Sunflower	0.810	0.656	138.45	618.40
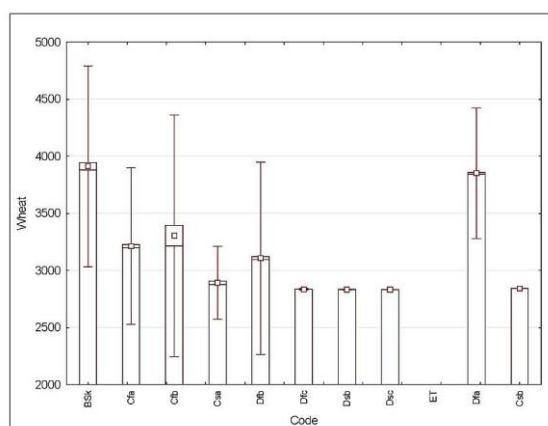
Figure 3. Box plot of wheat by code
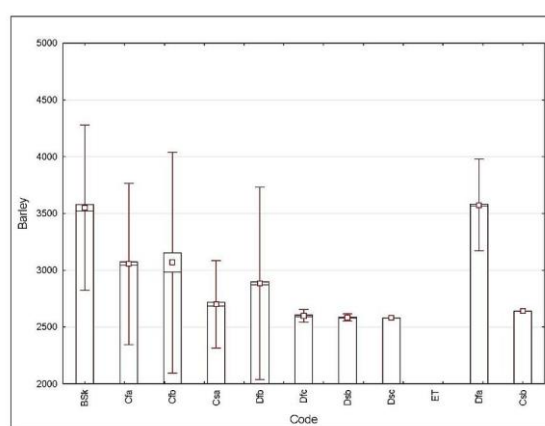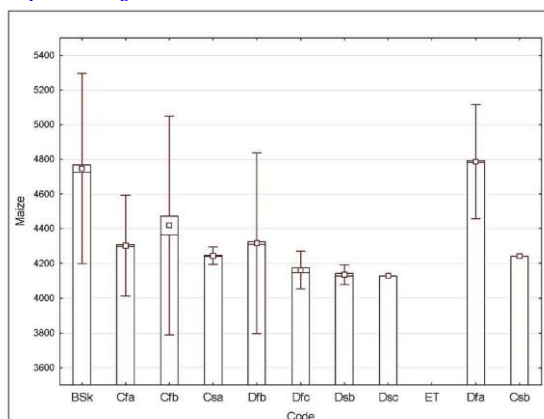

Figure 4. Box plot of barley by code

Figure 5. Box plot of maize by code
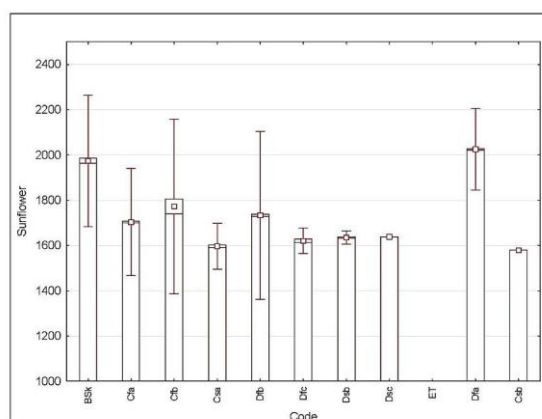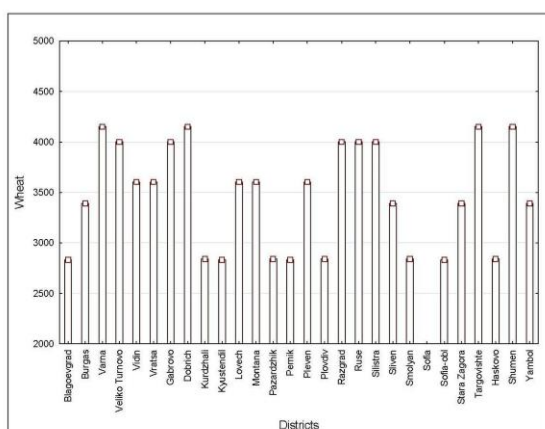

Figure 6. Box plot of sunflower by code

Figure 7. Box plot of wheat by districts
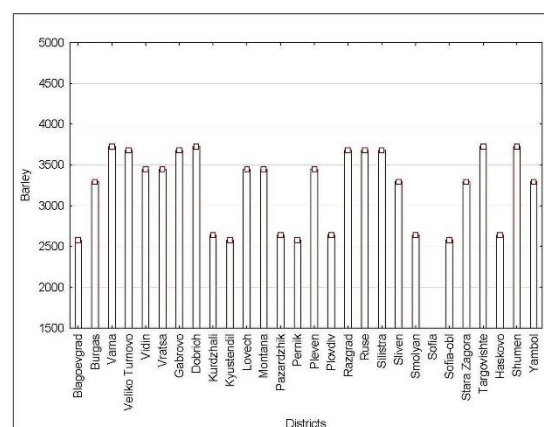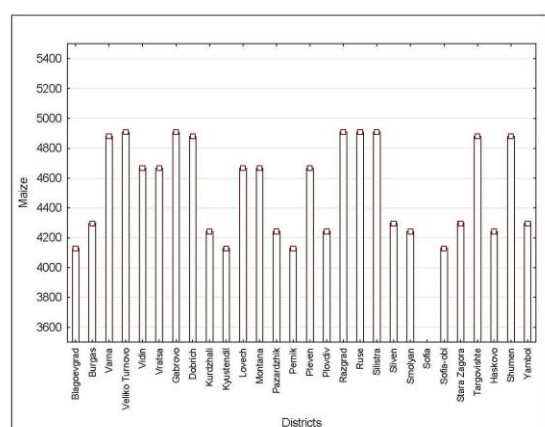

Figure 8. Box plot of barley by districts
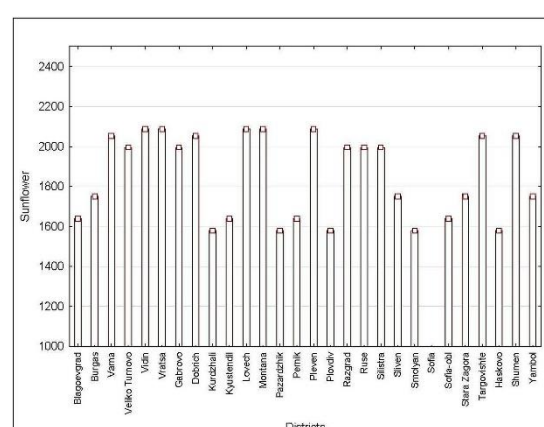

Figure 9. Box plot of maize by districts

Figure 10. Box plot of sunflower by districts

RESULTS

In our figures, the RGB colors used are provided between parentheses in Table 3 [3].

On Figure 1 the overlay of identified climate classes on Bulgaria base map gives the result of Lin's Climate Classifier (first approximation). The map contains only five classes. It is evident that the small number of locations is not sufficient to reveal all existing classification classes, which exist.

The next contour map which was derived from the analysis of the second set of data is given on Figure 2. It contains eleven climate classes and displays a diversity of climates over the territory of Bulgaria [total area of 110,993.6 km² (42,854.9 sq. mi)].

To solve the second task of the work we used data from the Bulgarian Ministry of Agriculture: average yield - kilogram per hectare of the four crops - wheat, barley, maize, and sunflower from the period 2001-2017 [18]. Data are given for six regions for planning and cover all 28 districts of the country [19].

The variables considered in regression equations usually can take values over some continuous range. Occasionally we must introduce a factor that has two or more distinct levels. For our case, data arise from eleven Köppen classes. In such a case we cannot set up a continuous scale for the variable "Koppen class". We assign to these variables some levels to take account of the fact they have separate deterministic effects on the response. Variables of this sort are usually called *dummy variables* [9]. In our case, we need to construct eleven dummy columns.

Table 4.
We are looking for regression equations for each crop from the type:

$$Y = b_1*BSk + b_2*Csa + b_3*Csb + b_4*Cfa + b_5*Cfb + b_6*Dsb + b_7*Dsc + b_8*Dfa + b_9*Dfb + b_{10}*Dfc + b_{11}*ET.$$ (Eqn. 1)

The application of that method resulted in the following multiple linear regression model to describe the relationship between wheat and 11 independent variables (Köppen codes). The equation of the fitted model is

$$Wheat = 3912*BSk - 1020*Csa - 1071*Csb - 698*Cfa - 606*Cfb - 1078*Dsb - 1079*Dsc - 60*Dfa - 803*Dfb - 1076*Dfc - 3912*ET.$$

(Eqn. 2)

In Table 5 are given exact results of the generalized linear regression analysis.

The results of the generalized linear regression analysis for the yield of barley, maize, and sunflower are presented in Tables 6, 7, and 8.

A summary of the statistical measures of regression models is given in Table 9. It is evident that maize yields have the highest coefficient of multiple correlation and coefficient of determination, which makes this crop most dependent on the climatic region of the studied ones. It is followed by sunflower, where the standard error of assessment is the lowest.

In Box plots, ranges of values of a selected variable are plotted separately for groups of cases defined by values of a grouping variable. The central tendency (median or mean) and range or variation statistics (e.g., quartiles, standard errors, or standard deviations) are computed for each group of cases, and the selected values are presented in the style as on the 2D Box plot. Below on Figures 3 to 6, the Box plots of the yield of four crops grouped by Köppen classes are presented.

The distribution of yield over the identified eleven climate classes for the four crops

shows that the highest yield can be received on territories characterized by Bsk and Dfa code. In these climate sites, the average yield of wheat reached 3900kg/ha, of barley 3500kg/ha, maize 4900kg/ha, and sunflower 2000kg/ha. For maize and sunflower maximum average yield under regions of Dfa code is even a little bit higher than those with Bsk code. The best climate for growing the four crops is Dfa, because of the smaller variation between the highest and lowest yield values. The next climate zone with high yields is Cfb, with the biggest deviation from the mean, followed by the Cfa and Dfb code zones with a little bit smaller deviation. The lowest yields encompass the Dfc, Dsb, Dsc, and Csb codes where the yield is near 2800, 2500, 4200, and 1600 kg/ha for wheat, barley, maize, and sunflower respectively.

The Box plots of mean yield from wheat, barley, maize, and sunflower grouped by districts are given on Figures 7 to 10.

The best districts to grow wheat are Varna, Veliko Turnovo, Gabrovo, Dobrich, Razgrad, Ruse, Silistra, Targovishte, and Shoumen, all they called "Dobrudzha". These districts occupy the Northeastern part of Bulgaria and generally coincide with Southern "Dobrudzha", which is located in the most Eastern part of the Danube plain. This determines the relief to be flat, with a tableland with a small altitude - up to about 200 meters.

It is no coincidence that "Dobrudzha" is called "The granary of Bulgaria" - the natural conditions, especially the soil and climate are extremely suitable for growing cereals and some industrial crops such as wheat, soybeans, maize, sunflower. In these districts, wheat yields are highest between 4000 and 4200 kg/ha. In the districts Vidin, Vratsa, Lovech, Montana, Pleven, (Northwestern Bulgaria), yields are near 3600 kg/ha and 3350 kg/ha in Burgas, Sliven, Stara Zagora and Yambol,

(Southeastern Bulgaria). The yields in Blagoevgrad, Kurdzhhali, Kyustendil, Pazardzhik, Pernik, Plovdiv, Smolyan, Sofia-obl, Haskovo, (Southwestern and South Bulgaria) is about 2800 kg/ha.

Average yields of barley are in two ranges: around 3500 kg/ha are obtained in Burgas, Varna, Veliko Tarnovo, Vidin, Vratsa, Gabrovo, Dobrich, Lovech, Montana, Pleven, Razgrad, Ruse, Silistra, Sliven, Stara Zagora, Targovishte, Shumen, and Yambol (East and North Bulgarian regions except Stara Zagora) and around 2500 kg/ha in Blagoevgrad, Kurdzhali, Kyustendil, Pazardjic, Pernik, Plovdiv, Smolyan, Sofia-obl and Haskovo (Southwestern and South Bulgaria). By nearly 1000 kg/ha the yields of barley are higher in North Bulgaria than in South Bulgaria.

Maize is divided, like wheat, into three yield regions according to the classification, characterized by 4900 kg/ha in Varna, Veliko Turnovo, Gabrovo, Dobrich, Razgrad, Ruse, Silistra, Targovishte, and Shoumen (Northeastern BG/Dobrudzha); 4600 kg/ha in Vidin, Vratsa, Lovech, Montana, Pleven (Northwestern BG), and 4200 kg/ha in Blagoevgrad, Kurdzhhali, Kyustendil, Pazardzhik, Pernik, Plovdiv, Smolyan, Sofia-obl, Haskovo, Burgas, Sliven, Stara Zagora and Yambol (South Bulgaria). Therefore, it is economically more profitable to grow maize in North Bulgaria with 400-700 kg/ha.

Sunflower yields, like barley, are combined around two values: 2025 kg/ha in Varna, Veliko Tarnovo, Vidin, Vratsa, Gabrovo, Dobrich, Lovech, Montana, Pleven, Razgrad, Ruse, Silistra, Targovishte, and Shoumen (North Bulgaria) and 1650 kg/ha Blagoevgrad, Burgas, Kurdzhhali, Kyustendil, Pazardzhik, Pernik, Plovdiv, Sliven Smolyan, Sofia-obl, Stara Zagora, Haskovo and Yambol (South Bulgaria). Thus, from the obtained results it can be summarized that North Bulgaria is more suitable for growing sunflower than South

with nearly 400 kg/ha greater yield opportunities.

DISCUSSION

The work presents a methodology for regionalization of climate according to the Köppen-Geiger climate classification and its use for linking the yields of basic agricultural crops with this classification. Results are related to the territory of Bulgaria, but the approach is applicable everywhere in the world. Extensive use of contouring, gridding, and surface mapping computer package, Geographic Information Systems, and advanced statistical methods allow obtaining reliable results and their appropriate interpretation. Regression equations using dummy variables present the dependent variable yield of crops as a function of Köppen classes. Graphical plots illustrated findings contribute to the agricultural economics of the country.

The study found significant differences between yields in North and South Bulgaria. Limiting values of the yields were obtained for the two parts of the country, divided lengthwise by the Balkan Mountains. The results show the need for future detailed research and regionalization of yields in North and South Bulgaria separately to obtain a clearer picture of the economically viable areas for growing the four main agricultural kinds of cereal.

DISCLAIMER

The mention of trade names or commercial products is for the information of the reader and does not constitute an endorsement or recommendation for use by the authors or their institutions.

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